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MECHANICAL REQUIREMENTS FOR SUCCESSFUL TRIPPING REACTIONS

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Falls and fall-related injuries are serious problems in the working population but even more so for the growing population of elderly people. Successful balance recovery after a trip appears to be a demanding task. It is quite likely that especially elderly individuals lack muscle strength to perform this task successfully. However, up to date no study has quantified the mechanical demands of recovering from a trip. Twelve young adult subjects repeatedly walked over a platform in which 21 obstacles were hidden. Each subject was tripped over one of these obstacles in at least 5 trials. A computer controlled appearance of the obstacles, so as to cause a trip at mid-swing. Kinematics and ground reaction forces on the stance limb were measured, and inverse dynamics was used to calculate joint moments during successful balance recovery. The net moments in the stance leg during successful recovery from tripping were high in comparison to literature data on the capacity of human subjects. This was true especially for moments about the ankle. The data suggest that strength training may be indicated in elderly subjects to reduce the risk of falling after a trip.

INTRODUCTION

Falls and fall-related injuries are common, costly and serious medical problems especially for the growing population of elderly people. One in three adults over 65 years of age falls once a year, mostly as the result of a trip or slip (Berg et al. 1997). Successful balance recovery after a trip appears to be a demanding task. It is quite likely that especially elderly individuals lack muscle strength to perform this task successfully. To reduce the occurrence of trip-related falls, identification of the factors that increase an individual's risk of falling following a mechanical disturbance during walking is needed.

Tripping reactions have been divided in two phases (Grabiner et al. 1996) the initial/early phase of the tripping response, from impact with the obstacle until placement of this foot, was coined the positioning phase. The second phase (support phase) is initiated at touchdown of the recovery foot. In the present paper we focus on the first phase. The term positioning phase suggests that the goal of this phase is to position the recovery foot by rapid reactions in the recovery limb. In line with this, most studies on tripping focused primarily on the reactions in the recovery limb either in terms of the kinematics (Grabiner et al. 1993, Eng et al. 1994, Grabiner *et al.* 1996, Pavol et al. 2001) or in terms of muscle activity (Eng *et al.* 1994, Schillings et al. 1999, Schillings et al. 2000). However, the stance limb plays an important role in recovery after tripping (Pijnappels et al. submitted). By pushing-off with the stance limb, time and clearance is provided for proper positioning of the recovery limb. Furthermore, generation of adequate joint moments in the stance limb, restrains the angular momentum of the body before the recovery limb hits the ground (Pijnappels *et al.* submitted).

In this study we attempt to describe the mechanical requirements for successful recovery reactions after a trip in terms of the kinetics of the stance limb, with the aim of elucidating potential limiting factors in the elderly.

METHODS

We had young adults walk numerous times over a platform in which 21 obstacles were hidden. In several trials, subjects were tripped over one of these obstacles. A computer controlled, based on online kinematic data, which one of these obstacles appeared at what time, so as to cause a trip repeatedly just before mid-swing, thus allowing us to focus on the elevating strategy.

Twelve volunteers (6 males, 6 females) with a mean age of 27 years (SD 4) participated in this study. Subjects were informed on the research procedures before they gave informed consent. Protocol and data collection were similar to those described in (Pijnappels *et al.* submitted). Subjects, wearing walking shoes, were instructed to walk at a self-selected speed over a platform of 12 meters. In the platform, a force plate was mounted and 21 aluminum obstacles of 15-cm height (28.5-cm width) were hidden over a total distance of 1.5 m. In about 10 of 60 walking trials, one of the obstacles suddenly appeared to catch the swing leg of the subject. At the start of each trial, subjects did not know whether an obstacle would appear, and if so, where. Online kinematic data of each trial were used to calculate the position and timing of the obstacle to appear, based on the subject's step length and velocity, so as to cause a trip in a specific phase of the stride cycle. The experimenter controlled whether or not an obstacle appeared, at which side (left or right), and in which phase. In this experiment, most trips were timed at mid-swing. A full-body safety harness, attached to a ceiling-mounted rail, ensured that subjects would not become injured should their recovery reaction be inadequate.

Gait kinematics were recorded during each trial using 4 Optotrak cameras arrays (Northern Digital). Motion of 12 infrared-light emitting markers was tracked. The markers were placed bilaterally on the anatomical landmarks heel, metatarsophalangeal joint (MTP5), lateral malleolus, lateral epicondyle and trochanter major of the femur, and acromial process. The coordinates of these landmarks defined 7 body segments: 2 feet, 2 lower legs, 2 upper legs and a head-arms-trunk (HAT) segment. Ground reactions forces on the right foot were measured with a custom-made strain gauge force plate (1x1m). Software developed in LabVIEW (National Instruments) was used to synchronize and collect the kinematic data and ground reaction forces at a sample frequency of 100 Hz and to control the appearance of obstacles hidden in the walkway.

For each subject, 5 left leg tripping trials at mid-swing were selected (in 2 subjects only 3 tripping trials were available). Heel strike (HS) and toe-off (TO) were detected on the basis of kinematic data, because force plate data were not available for the left foot. HS coincided with a local minimum in the vertical velocity component of the toe marker and TO coincided with a local maximum in the vertical velocity component of the heel marker (Pijnappels et al. 2001). Impact of the foot with the obstacle coincided with a local minimum in the jerk of the toe marker in the walking direction. Based on HS, TO and obstacle-foot contact events, data were analyzed in the sagittal plane after smoothing with a mono-directional second order low-pass Butterworth filter with a cutoff frequency of 8 Hz. Uni-directional filtering preserved the timing of the start of obstacle-foot contact onto the data. Joint forces and moments were calculated using an inverse dynamics model. The inertial parameters of each segment (mass, position of the segmental center of mass and the segmental moment of inertia) were calculated per subject, according to Plagenhoef (1983). To study the mechanical requirements of recovery reactions, we looked specifically at the peak joint moments and the rates of change in generating these moments.

In 9 subjects, net moments when landing on the swing limb (support phase) in right leg trips were calculated.

RESULTS

The subjects walked at a speed of 1.61 (SD 0.15) m/s and frequency of 117 (SD 4.5) steps/min. Tripping reactions were induced at 39 (SD 3.8) % of the normal swing phase duration. Typically after tripping in this particular phase of the gait cycle, subjects performed an elevating recovery strategy. Selected trials were all successful recoveries. Immediately after collision the obstructed swing leg was elevated over the obstacle while the stance limb provided prolonged push-off.

After tripping, the ankle moment of the stance limb, was increased relative to normal push-off. Furthermore, whereas normally during push-off an extension moment is observed at the knee joint, after tripping a flexion moment can be seen. The opposite was observed in the hip, whereas normally a flexion moment is observed, a strong extension moment is seen after tripping. The peak hip extension moment and knee flexion moment after tripping, were found to be in the range of moments during normal walking. The peak ankle moment, however, was very high after tripping (Table 1). The rate of change of the moment in the first 50 ms was also highest in ankle of the stance limb ankle (Table 1).

Table 1. Peak joint moments for both stance and swing limb after tripping, averaged over trials and subject. SD between brackets.

	Stance leg			Swing leg positioning		
	ankle	knee	hip	ankle	knee	hip
moment (Nm)	204 (41)	-55 (21)	53 (21)	-21 (6)	29 (9)	-43 (8)
moment rate (Nm/s)	1340 (374)	-571 (212)	557 (286)		support (n=9)	
moment (Nm)				149 (49)	142 (40)	179 (50)

Peak joint moments in the swing limb were much less high than in the stance limb during the first phases of recovery. Rates of change in the peak limb were mainly determined by the impact force on the swing limb and are therefore not reported. During the support phase high extension moments were found in the swing limb, on which subjects land in this phase. These values are higher than in normal walking.

DISCUSSION

This study investigated the mechanical demands in the primary reactions after tripping in both the obstructed swing limb and the push-off limb. It appeared that in the initial phase of recovery, the mechanical requirements were larger in the stance limb than in the swing limb. Although during push-off, no important joint angle deviations were seen in the stance limb (substantial knee flexion was first seen in the swing phase after push-off), the joint moments generated in during push-off, were large. Especially a large ankle flexion moment, generated by triceps surae muscles and a hip extension moment, generated by hamstring activity, brought about the necessary push-off reaction. When landing on the swing (recovery) limb in the second phase of the recovery reaction, high net moments were found in this limb as well. Given its magnitude and rate of rise, the ankle moment in the stance leg is most likely to be a limiting factor in the response.

The hip and knee joint moments in the stance limb during push-off were directed opposite to those during the push-off in normal walking. Similarly in slipping knee flexion and hip extension moments were found, instead of respectively extension and flexion moments during normal walking (Cham and Redfern 2001, Redfern et al. 2001). A knee extension moment and hip flexion moment, together with the increased ankle plantar flexion moment, result in a ground reaction force that is increased in magnitude and directed more forward. In line with earlier findings (Pijnappels *et al.* submitted), this indicates an attempt to generate an external moment to restrain or even counteract the forward angular momentum of the body already in the first phase of the tripping response. This response is thus highly functional and hence limitations in this response may increase the risk of falling as a consequence of a trip.

The net moments in the stance leg during successful recovery from tripping were high in comparison to literature data on the capacity of human subjects. This is true especially for moments about the ankle (LeBlanc et al. 1988, Trappe et al. 1996, Porter and Vandervoort 1997, Dowson et al. 1998, Gajdosik et al. 1999, Trappe et al. 2001, Pavol et al. 2002). The peak ankle moment was higher than the isometric and isokinetic voluntary maximum moments in a compilation of data from the literature (Figure 1) and close to the peak in maximal one-legged jumps (van Soest et al. 1985).

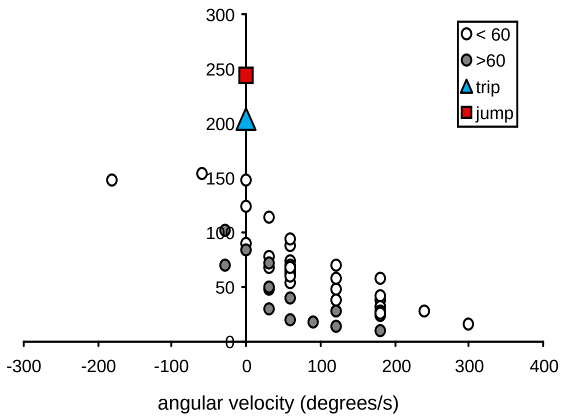

Figure 1. Maximum ankle extension moments as a function of ankle extension velocity from a compilation of published sources for subjects under 60 and over 60 years of age and the maximum moments found during tripping in the present study and one-legged jumping (van Soest *et al.* 1985).

The peak value and rate of change of the ankle moment exceed the isometric capacity of a group of elderly females (Pavol *et al.* 2002) by factors of about 2.4 and 5.6 respectively. Perhaps these factors are artificially high because no correction was made for joint angle, subject characteristics, and the fact that voluntary activation in isometric conditions is not necessarily maximal. Nevertheless the data show that high moments are required, which could constitute a problem for the elderly. Strength training may be indicated in elderly subjects to reduce the risk of falling after a trip.

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